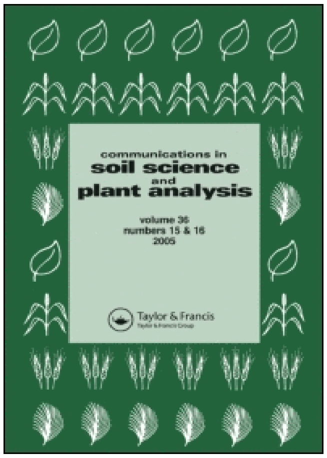

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Evaluation of Continuous In Situ Monitoring of Soil Changes with Varying Flooding Regimes

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Evaluation of Continuous In Situ Monitoring of Soil Changes with Varying Flooding Regimes

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Abstract: To support investigations of flood tolerance occurring at a field-based research facility, changes in soil volumetric water content, temperature, redox potential, dissolved oxygen content, and pH over the course of flood events were monitored. Electronic sensors connected to dataloggers for continuous monitoring of these parameters were installed, and soil redox potential and pH were also monitored manually for comparison. Soil volumetric water content showed that soils became saturated quickly following inundation. Soil redox potentials revealed a reduction of the soil with inundation; however, stagnant water treatments did not result in lower redox potentials than flowing water treatments. Similarly, dissolved oxygen content was not lower in the stagnant water treatment. The automated and manual systems detected similar trends in redox potential response to flooding; however, redox potentials measured manually were generally higher and significantly different from those obtained with the automated system. Anomalous readings were

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detected with the automated measurement of soil pH, indicating further need for improvement of this system.

Keywords: Flooding, in situ monitoring, long-term monitoring, redox potential, soil inundation, soil pH

INTRODUCTION

Preservation and restoration of wetlands have become imperative with increasing evidence of the services these ecosystems provide. As an example, riparian wetlands moderate river levels and purify runoff from adjacent lands, as well as provide habitat for numerous wildlife species. Missouri has approximately 260,200 hectares (643,000 acres) of wetlands, most of which are associated with rivers and streams. Periodic flooding of these rivers and floodplains commonly occurs during times of heavy rainfall. Such floods can result in stagnant or flowing water over soils supporting agricultural fields or forests. Soil inundation during flooding transforms the soil, creating an anaerobic environment and increasing the presence of reduced mineral ions. Flooding (Lockaby, Murphy, and Somers 1996) and water table elevation (Hefting et al. 2004) have been shown to alter nitrogen dynamics and thus influence nutrient availability, alter plant growth, and delay or reduce plant reproduction.

The increasing interest in riparian and wetland systems prompted the development of the Flood Tolerance Laboratory (FTL), a state-of-the-science outdoor facility designed for quantifying the flood tolerance of hardwood seedlings and groundcover plant species. At the FTL, floodwater depth, duration, and flow rate can be regulated to experimentally simulate the impact of different flood regimes. Because flood tolerance is largely the physiological adaptation of plants to anoxic conditions, toxic substances, and other associated changes in soil properties induced by flooding, quantifying changes occurring below ground is imperative for quantifying flood tolerance.

Redox potential measurements provide one way to quantify the magnitude of reducing conditions in the soil environment and thereby assess nutrient availability in a flooded system (Patrick, Gambrell, and Faulkner 1996; Owens et al. 2005). Redox potential is a measure of the tendency of a biogeochemical system to receive or supply electrons (Hinchey and Schaffner 2005). Because a number of redox couples act simultaneously within the soil system, redox potential provides a semiqualitative assessment (Austin and Huddleston 1999; Gao et al. 2002; van Bochove, Beauchemin, and Thériault 2002; Hinchey and Schaffner 2005; Owens et al. 2005). However, this measure can allow differentiation between oxic and anoxic soil conditions and the monitoring of the progressive development of reduced conditions (Gao et al. 2002).

A number of studies (Austin and Huddleston 1999; van Bochove, Beauchemin, and Thériault 2002; Mansfeldt 2003; Wafer, Richards, and Osmond 2004) have shown limited success in long-term monitoring of soil redox conditions with platinum electrodes. Wafer, Richards, and Osmond (2004) demonstrated that after 19 months in the field, 98% of their electrodes were functioning satisfactorily, and Austin and Huddleston (1999) had a similar rate of success 3 and 5 years after installation of electrodes. However, these studies and others caution that permanently installed electrodes may become contaminated over time, thereby leading to erroneous readings (Austin and Huddleston 1999; Mansfeldt 2003; Hinchey and Schaffner 2005). Electrode rupture or leakage also results in unreliable readings (Mansfeldt 2003). Other potential problems that may arise during long-term monitoring include calibration drift, signal disruption and electronic failure from water leakage into the system, lack of circulation around an electrode or membrane, and maintenance and monitoring costs.

Despite some obvious pitfalls, permanent installation and automated monitoring of electrodes may have advantages over manual measurements. Manual measurements may be impractical because of location and accessibility of field sites during periods of inundation; fluctuations that occur with weather and flooding may therefore be overlooked (Vorenhout et al. 2004). In addition, manual measurements may be affected by the presence of the operator because operator presence may change soil pressure, thereby affecting redox readings (Vorenhout et al. 2004). Permanent installation of electrodes permits frequent measurements over short time intervals, allowing for identification of diurnal fluctuations. In addition, the system can be monitored from a distance, creating fewer disturbances. Other advantages of automated systems include the ability to store data, adjust the time of sampling, control sensor operation, and monitor operation of each sensor.

The objectives of this study were twofold. The first was to examine the performance of an automated system for in situ monitoring of the changes in redox potential and pH as well as a number of other soil properties affected by flooding including soil water content, temperature, and dissolved oxygen content. The second objective was to compare the effects of flood duration and flow rate on soil properties in the FTL.

MATERIALS AND METHODS

Study Site

This study was conducted at the FTL at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, Missouri (39° 0′ 0″ N, 92° 46′ 0″ W) as a part of research examining flood tolerance of hardwood seedlings and groundcover plant species. The FTL is an outdoor research facility constructed on a wide terrace floodplain adjacent to Sulfur Creek. A limestone-covered county road runs on the north side of the research facility, allowing access. The FTL consists of 12 6-m × 180-m parallel channels; each channel can be manipulated independently of adjacent channels to allow for various flood treatments (i.e., changing depth, flow rate, and duration of flooding). Channels are numbered sequentially (1–12) from north to south. Soil removed in the creation of a retention pond for the facility was used to create berms (2 m high and 6 m wide) between the channels; this allowed for minimal disturbance to the soils within the channels. Water is pumped underground from the retention pond to the inlet end of the channels, and in flowing-flood treatments, water circulates between the pond and the channels, flowing from the inlet to the outlet (pond) end.

Site Description: Soil Characteristics

Soil properties are not consistent across the FTL (Table 1). Soil textural classes range from silt loam to silty clay loam, with the silt fraction generally increasing and clay fraction generally decreasing with proximity to the creek. All channels display evidence of past plowing (i.e., all have an Ap horizon), 8 of 12 channels have Bg horizons (gleyed condition), and 3 of the channels have Bt horizons (clay accumulations). Channels with Bt horizons are closer to the road, whereas channels with Bg horizons are closer to the creek. Soil pH, cation exchange capacity (CEC), and base saturation are all slightly higher in the channels adjacent to the road, possibly because it is limestone covered. Total organic carbon (C) content is fairly consistent across the channels and is generally low.

Flood Treatments

Four flood treatments were evaluated: (i) no flood (control), (ii) 3 weeks of flowing water maintained at 15 cm, (iii) 5 weeks of flowing water maintained at 15 cm, and (iv) 5 weeks of stagnant water maintained at 15 cm. Flooding of all experimental channels was initiated on 23 May 2005; 3-week-flowing channels were drained on June 13, and 5-week-flowing and 5-week-stagnant channels were drained on June 27. Automated monitoring began with the flooding of the channels and continued until July 4, allowing us to capture changes that occurred not only with the flooding but also with dry-down of the channels. The experimental design was a randomized complete block with three blocks arranged in a north–south direction; each block contains each of the four treatments.

Automated Monitoring of the Flood Tolerance Laboratory

To automate the monitoring of changes in soil volumetric water content, temperature, redox potential, dissolved oxygen content, and pH in response to flood treatments, electronic sensors connected to dataloggers were installed in each

Table 1. Selected soil characteristics and classification information for soils associated with the Ap horizon in each of the 12 channels of the FTL

Channel	Soil classification	Textural class	Texture			Total organic C (%)	pH 1:1 (H_2O)	CEC ($cmol_c$ Kg^{-1})	Base saturation
			Clay (%)	Silt (%)	Sand (%)				
1	Fine, mixed, active, mesic Aquertic Hapludalfs	Silty clay loam	35.2	60.6	4.2	1.0	7.4	28.0	88
2	Fine, mixed, superactive, nonacid, mesic Aquertic Hapludalfs	Silty clay loam	29.5	65.1	5.4	1.4	7.5	23.0	83
3	Fine-silty, mixed, superactive, nonacid, mesic Typic Endoaqualfs	Silty clay loam	29.9	64.0	6.1	1.0	7.5	25.0	88
4	Fine, mixed, superactive, nonacid, mesic Aeric Endoaqualfs	Silt loam	22.4	70.6	7.1	0.9	7.6	20.1	86
5	Fine-silty, mixed, superactive, nonacid, mesic Mollic Fluvaquents	Silty clay	43.1	53.4	3.4	1.0	7.3	18.7	85
6	Fine-silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts	Silt loam	21.1	74.0	4.9	0.8	7.2	18.7	86

7	Fine-silty, mixed, super-active, nonacid, mesic Mollic Udifluvents	Silt loam	24.1	70.9	5.0	1.1	7.0	20.5	88
8	Fine-silty, mixed, super-active, nonacid, mesic Typic Fluvaquents	Silt loam	23.1	70.6	6.3	1.2	6.3	21.7	77
9	Fine-silty, mixed, super-active, nonacid, mesic Aeric Fluvaquents	Silt loam	20.2	73.9	5.9	1.0	6.4	21.8	76
10	Fine-silty, mixed, super-active, nonacid, mesic Aeric Fluvaquents	Silt loam	23.2	70.7	6.2	1.3	6.1	20.7	71
11	Fine-silty, mixed, super-active, nonacid, mesic Aquic Udifluvents	Silt loam	19.9	73.7	6.4	1.1	5.9	18.9	77
12	Fine-silty, mixed, super-active, nonacid, mesic Mollic Udifluvents	Silt loam	21.5	63.0	15.5	1.2	6.3	20.8	78

Note. Data for soil samples of the Ap horizon (0–25 cm) from the sensor end of each channel.

channel in May 2005. Three CR23X micrologger (Campbell Scientific, Logan, Utah) stations in waterproof enclosures were installed, one between channels 2 and 3, one between channels 6 and 7, and one between channels 10 and 11. Each micrologger received signals from four channels and was connected to an AM16/32A 16 channel multiplexer. The multiplexer increased the capacity of the datalogger, allowing for the connection of more sensors for possible expansion of the system. The microloggers were programmed such that readings were taken every 30 s; readings were then averaged for the hour and recorded in the datalogger memory. The micrologger installed between channels 10 and 11 was also equipped to measure ambient air temperature and rainfall. A 107-L temperature probe, housed within a six-plate radiation shield, was used to measure ambient air temperature. The radiation shield reflects solar radiation, keeping the probe at or near ambient temperature. Rainfall information was collected using a Texas Electronics 15.24-cm tipping bucket rain gage (0.0254-cm tip). Sensors for the monitoring of soil volumetric water content, temperature, redox potential, dissolved oxygen content, and pH were installed near the outlet end of the channels. To protect the cables from rodents, cables were threaded through PVC pipe that was buried in berms separating the channels.

Soil volumetric water content was monitored at two depths (5 and 15 cm) using model CS616 water content reflectometer (Campbell Scientific, Logan, Utah). This sensor can be buried at any orientation to the surface (in this case, the sensor was parallel to the surface) and consisted of two 30-cm stainless steel rods connected to measurement electronics (www.campbellsci.com). The measuring range of volumetric water content for this sensor was 0% to saturation. Similarly, soil temperature was monitored at two depths (5 and 15 cm) using a model 107-L temperature probe (Campbell Scientific, Logan, Utah). This sensor can be used to measure the temperature of a variety of media, including soil. It consists of a thermistor encapsulated in a cylindrical housing and is capable of measuring temperatures from -35 to $+50^{\circ}$C (www.campbellsci.com).

Dissolved oxygen was measured at the soil/water interface using submersible galvanic dissolved oxygen (model CS511) sensors manufactured by Sensorex (Garden Grove, Calif.) and distributed by Campbell Scientific (Logan, Utah). This sensor was equipped with a zinc anode and a silver cathode (both internal) covered by a Teflon® membrane. The range of the sensor was 0–20 mg L^{-1} or 0 to 200% saturation (www.campbellsci.com). Sensor output was 1.65 mV per mg L^{-1} (± 0.45 mV), and this factor was used to convert mV to mg L^{-1} for reporting. Because this sensor was equipped with an in-line thermistor, additional conversions due to temperature were not necessary.

Soil redox potential and soil pH were measured at a depth of 5 cm using flat-surface, self-cleaning electrodes manufactured by Sensorex (Garden Grove, Calif.). These sensors are designed for measurements in systems with high concentrations of suspended solids, making them also suitable for soil systems. Both electrodes are combination electrodes (ORP reference or pH reference) with double reference junctions; the oxidation reduction potential (ORP) electrode has a platinum standard whereas the pH electrode is equipped with a pH-responsive flat glass surface. The ORP electrode has a range of ± 2000 mV, and the pH electrode has a range of 0–14 pH (www.sensorex.com). Because of the travel distance of the signal (approximately 90 m from the electrode in the channel to the datalogger), both ORP and pH electrodes were attached to PHAMP-1 battery-powered pH/ORP pre-amplifiers to intensify the signals. Replacement of the electrodes is facilitated by plug-in cable connections.

Prior to installation, both ORP and pH electrodes were tested to establish if the system was functioning properly. Tests were conducted to determine if the signal was reaching the datalogger and whether the electrode was providing accurate readings. An ORP standard solution (Orion 967901) and tap water were used to test the ORP electrodes. Electrodes with an silver (Ag)/silver chloride (AgCl) reference should produce a reading of approximately 215 mV for this standard solution; tap water was tested to determine if the electrodes responded to changes in the system. The ORP standard solution was also used to calibrate redox potentials to the standard hydrogen electrode. The pH electrodes were calibrated using pH 4 and pH 7 buffers.

Manual Monitoring of the Flood Tolerance Laboratory

In addition to the automated monitoring system, manual measurements of soil redox potential and pH were taken twice each week (Monday and Friday mornings) during the flood treatments and the post-flood recovery period. For this monitoring, portable, waterproof Oakton 300 series meters (Cole-Parmer, Vernon Hills, Ill.) were used. These meters have a pH range of -2 to 16 pH with a resolution of 0.1/0.01 pH, and an ORP millivolt range of ± 2000mV with a resolution of 0.1 to ± 399.9mV and a resolution of 1 mV when outside this range. Submersible, double-junction, 0.9-m pH and ORP electrodes (Cole-Parmer, Vernon Hills, Ill.) were used to measure pH and ORP.

Statistical Analysis

Changes in soil parameters (volumetric water content, temperature, redox potential, dissolved oxygen content, and pH) over time due to the flood treatments as monitored by the automated system and by the manual approach were analyzed using ANOVA (Proc MIXED) with a repeated statement (SAS 9.1, SAS Institute Inc. 2002–2003). This procedure represents a simplification of the generalized linear model (Proc GLM) but with a wider class of covariance structures and improved ability to handle missing values. The compound symmetry covariance structure was used for this analysis. Data is reported as least square means; comparisons of least square means were made using PDIFF ($\alpha = 0.05$).

Automated and manual readings of soil redox and pH were evaluated. However, because the exact time of the manual readings was not recorded (i.e., all readings were taken before noon, but the precise hour was not documented), direct comparisons between the manual and automated readings were not possible. Automated readings recorded between 7 a.m. and noon on the days of the manual readings were averaged, and 95% confidence intervals were calculated. Manual readings were examined to see if values were within these confidence intervals. Correlation and regression analysis (Proc CORR and Proc REG, SAS 9.1, SAS Institute Inc. 2002–2003) were used to determine the association between average automated and manual sensor readings.

RESULTS AND DISCUSSION

Volumetric Water Content

Soils within the flooded channels became saturated soon after implementation of the experimental treatments (Figure 1). Once these soils were saturated, water content varied little for each treatment over time, only decreasing slightly with removal of flood treatments. Differences in soil water content were observed between the two depths; these differences were likely caused by variation in bulk density due to changes in pore volume or soil texture with depth.

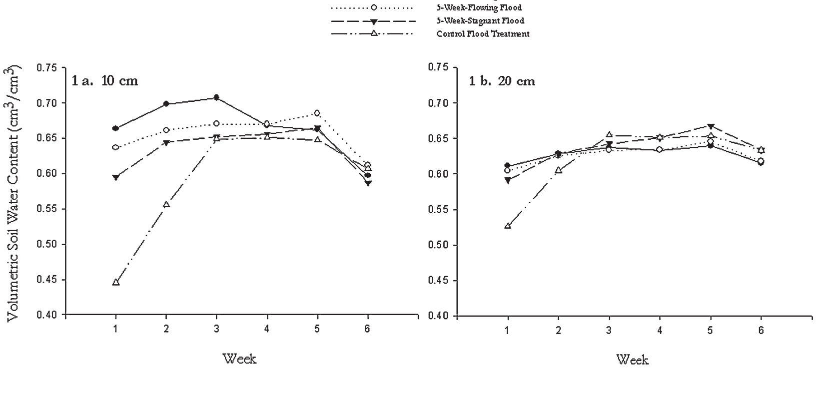

Figure 1. Soil volumetric water content at 10 cm (a) and 20 cm (b) by treatment measured by automated sensors for a 6-week period. Weekly averages for each treatment were calculated by combining hourly data from replicate channels. Week 1: May 23–29, week 2: May 30–June 5, week 3: June 6–12, week 4: June 13–19, week 5: June 20–26, and week 6: June 27–July 3.

Data from the first 2 weeks of monitoring showed soils of the flooded channels with considerably higher volumetric water content than the control channels, particularly at the 10-cm depth. During the first week, the water content of the flooded channels was $0.14-0.21\ cm^3/cm^3$ higher than the control channels at 10 cm and $0.07-0.09\ cm^3/cm^3$ higher at 20 cm. Differences were less pronounced during the second week, with the water content of the flooded channels $0.09-0.14\ cm^3/cm^3$ higher than the control channels at 10 cm and $0.02\ cm^3/cm^3$ higher at 20 cm. By week 3 of flooding, differences between the control and flooded channels were absent regardless of depth (Figure 1). The increase in soil water content of the control channels at week 3 may be attributed to a period of abundant rainfall (June 3–13) (Figure 2a) or due to seepage from adjacent flooded channels. Because increases in soil water content in the control channels were observed between weeks 1 and 2 when rainfall was slight, seepage from adjacent channels cannot be ruled out. Control channels were notably moist by the termination of the experiment; for example, indentations in the soil created from walking in the channels would slowly fill with water.

The ANOVA results revealed significant main effects (flood treatment and time) but no significant interaction for soil water content at 10 cm (flood treatment: $F = 3.75$, $P < 0.02$; time: $F = 3.02$, $P < 0.02$). The ANOVA results also revealed a significant time effect for soil moisture at 20 cm ($F = 3.06$, $P < 0.02$) but no significant flood treatment effect or flood treatment $\times$ time interaction.

Soil Temperature

Soil temperature readings at two depths (10 cm and 20 cm) showed a gradual increase in temperature over the course of the experiment (Figure 3). Becuase the experiment spanned 6 weeks beginning in late May and ending in early

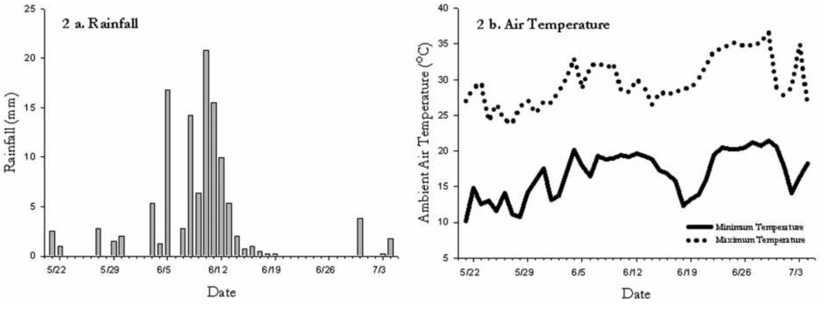

Figure 2. Rainfall (a) and ambient air temperature (b) for a 6-week period (May 22–July 4 2005). Data were collected by automated sensors with readings taken every 30 s and averaged for the hour. Rainfall is reported as total amount of precipitation received for a particular date; temperature is reported as daily minimum and maximum.

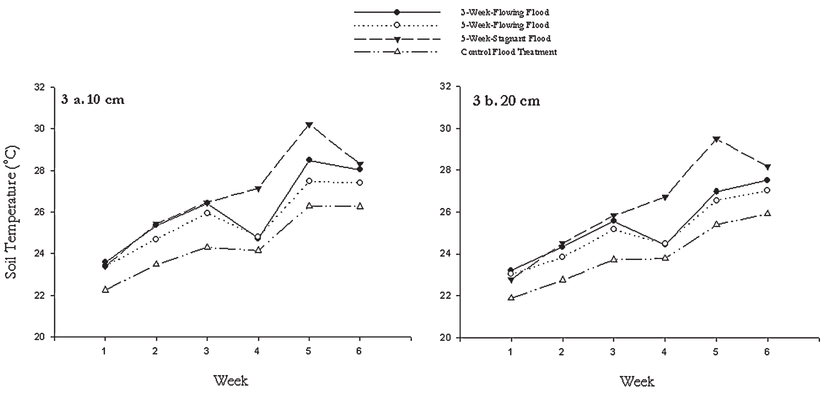

Figure 3. Soil temperature at 10 cm (a) and 20 cm (b) by treatment measured by automated sensors for a 6-week period. Weekly averages for each treatment were calculated by combining hourly data from replicate channels. Week 1: May 23–29, week 2: May 30–June 5, week 3: June 6–12, week 4: June 13–19, week 5: June 20–26, and week 6: June 27–July 3.

July, this increasing trend was not surprising. A similar increasing trend in ambient air temperatures was also observed (Figure 2b).

Regardless of depth, soils in the control channels were slightly cooler than soils in the flooded channels (Figure 3). A combination of factors contributed to higher soil temperatures in the flooded channels. The flooded channels had darker surfaces because they supported less vegetation than the controls, causing the flooded channels to absorb more solar radiation and to become warmer. The higher specific heat of the flooded channels caused them to retain more heat during the night than did the controls.

Soil temperature data for the 3-week-flowing and the 5-week-stagnant treatments were similar at both depths early in the recording period, whereas the 5-week-flowing treatment exhibited slightly lower temperatures. At week 4, temperatures in the flowing treatments decreased, and the 5-week-stagnant temperatures remained consistent with the general trend of increasing soil temperature readings. The observed drop in temperature for the flowing channels may be related to the heavy rains recorded during the previous 10 days (Figure 2a). Soils in channels under the flowing flood treatments would be expected to be cooler than those under stagnant flood treatments because of dissipation of energy due to water movement. ANOVA results revealed a significant flood treatment × time interaction for soil temperature at both depths (10 cm: $F = 2.03$, $P < 0.04$; 20 cm: $F = 4.91$, $P < 0.0001$); both main effects were also significant at both depths.

Soil Redox Potential and Dissolved Oxygen

In general, redox levels decreased after initiation of flooding and increased following dry-down of the channels (Figure 4). In the control channels, the

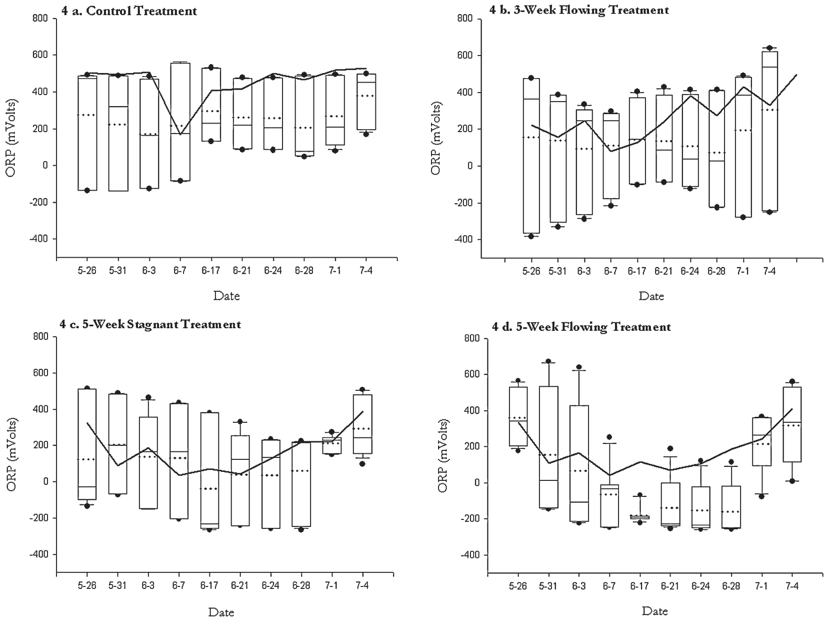

Figure 4. Soil redox potential measured by the automated sensors (box plots) and manual sensors (line) for a 6-week period (May 26–July 4 2005). For automated sensors, weekly averages were calculated by combining hourly values between 7 a.m. and 12:00 p.m. from replicate channels. For replicate channels, the boxes depict the 25th and 75th percentiles, the whiskers indicate 10th and 90th percentiles, the solid line represents the median, and the dotted line represents the mean. Manual readings were measured once during the period sampled by the automated sensors; data points represent the average reading for replicated channels under the designated treatments.

average redox levels remained relatively constant over time (Figure 4a). Average redox levels recorded with the automated sensors ranged from 217 to 287 mV over the course of 6 weeks, whereas those recorded with handheld meters were considerably higher and ranged from 405 to 530 mV (except approximately 3 weeks into the experiment). The differences between the automated and manual readings were notable because the automated sensor readings for the control channels were within the "suboxic" range, indicating that the soils of these channels were neither anaerobic nor well oxygenated. However, manual readings for these channels generally fell within the oxic range, indicating that the soils were well oxygenated.

Average redox potentials for 3-week-flowing treatment were lower than the control channels (Figure 4b). Initial average redox potentials revealed suboxic conditions in soils under this treatment regards of monitoring method (automated average = 167 mV; manual average = 223 mV). Redox potentials decreased to their lowest points during the second and third week of the flood (lowest automated average = 58 mV; lowest manual average = 81.5 mV), and anoxic conditions were observed during this time period. With the removal of the flood treatment at the end of week 3/beginning of week 4, the redox levels increased; however, this increase was not consistent. At termination of the experiment, automated readings indicated that the soils were suboxic (average reading = 155 mV), whereas manual readings indicated that soils were oxic (average reading = 518 mV). As was the case with the control channels, a discrepancy between the automated and manual system was noted. The manual readings were higher than those recorded by the automated sensors.

As expected, the lowest redox potentials were recorded, and anoxic conditions were observed in the 5-week flood channels (Figures 4c and 4d). For each 5-week treatment, the manual readings were very similar to each other and considerably higher than the automated readings (Figures 4c and 4d). The average manual readings ranged from 326 to 334 mV and decreased to 34 to 43 mV during the first two weeks of flooding; at termination, manual readings ranged from 506 to 539 mV. Average automated readings for the 5-week-stagnant treatment decreased from 301 mV to 24 mV by the fourth week and then increased to 156 mV at the termination of monitoring (Figure 4c). Unexpectedly, the automated readings in the 5-week-flowing treatment were lower than in the 5-week-stagnant treatment. Redox readings for the 5-week-flowing treatment decreased from 326 mV to −173.68 by the fourth week and subsequently increased to 120 mV at the termination of monitoring (Figure 4d). We anticipated lower redox levels for the 5-week-stagnant treatment than for the 5-week-flowing treatment because the movement of water through the flowing channels should have maintained higher oxygen levels in the flood water, thereby increasing the diffusion of dissolved oxygen into the soil.

Dissolved oxygen readings may help explain the redox potential results. First, dissolved oxygen readings showed a marked difference between the soils of the control channels and the soils of the channels exposed to the various flood treatments. Dissolved oxygen levels were generally high in control channels, averaging 12–14 mg L^{-1}, with the exception of weeks 2 and 3 where dissolved oxygen fell to 7.21 mg L^{-1} and 9.81 mg L^{-1} respectively (Figure 5). Lower dissolved oxygen levels were expected and observed under the flood treatments. As water-filled pore space increases, a corresponding decrease in air-filled pore space would be expected. ANOVA results indicated a significant treatment effect ($F = 12.28$, $P < 0.0001$); however, time and the flood treatment × time interaction were not significant. Second, although dissolved oxygen levels in the flooded channels did not vary notably by treatment, the 5-week-flowing treatment had consistently lower dissolved oxygen readings than the other flood treatments (Figure 5). These lower dissolved oxygen readings could help explain the lower redox potential readings of the 5-week-flowing treatment.

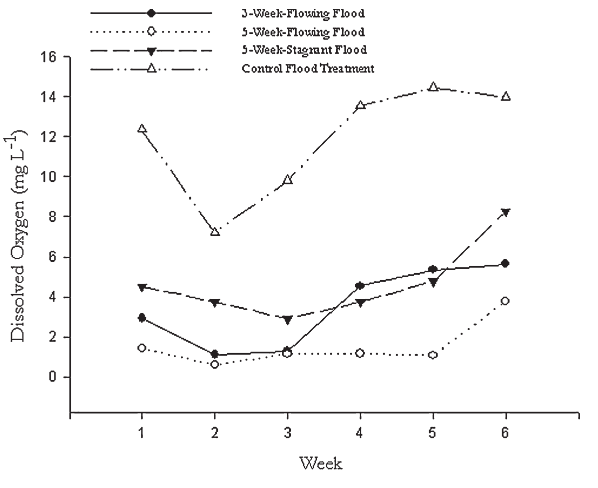

Figure 5. Dissolved oxygen content by treatments measured by automated sensors for a 6-week period. Weekly averages for each treatment were calculated by combining hourly data from replicate channels. Week 1: May 23–29, week 2: May 30–June 5, week 3: June 6–12, week 4: June 13–19, week 5: June 20–26, and week 6: June 27–July 3.

The overall patterns of observed redox potential response to different flood treatments were similar to those described in other systems. For example, Austin and Huddleston (1999) observed that in unsaturated soils, the redox potential fluctuated in response to rainfall. Whereas redox potentials in the control channels were relatively constant over the course of the experimental period, with manual monitoring we detected a decline in redox potential during a time of heavy rainfall. Austin and Huddleston (1999) and D'Amore et al. (2004) both described a rapid decline in redox potentials with saturation and a subsequent rise in redox potentials with desaturation and reaeration of the soil. In addition, D'Amore, Stewart, and Huddleston (2004) and Mansfeldt (2003) indicated that lower redox potentials were associated with longer periods of saturation. Similarly, a decline in redox potential with inundation and a rise in redox potentials with the dry-down of the channels were observed in this study. In addition, redox potentials were lower in the 5-week floods than in the 3-week flood.

The average automated readings were usually lower and much more variable than the average manual readings. This variation may be due to sensor irregularities. For example, channel 12, a channel under the 5-week-stagnant treatment, had consistently high redox potentials and failed to show the decrease in redox potential expected with inundation. On the other hand, all three channels of the 5-week-flowing treatment displayed the expected decrease in redox potential with flooding. Sensor irregularities may also explain why the automated readings for the control and 3-week-flowing treatments were lower than the manual readings. Channel 7 (a control channel) and channel 5 (a 3-week-flowing channel) both had redox readings that were considerably lower than the other channels under their respective treatments. These readings lower treatment averages and thus may be the cause of significant differences observed between sampling techniques.

The ANOVA results for the automated sensors showed no significant differences in redox levels due to flood treatment, time, or flood treatment × time interaction. High variability may have contributed to the nonsignificant results. The ANOVA results for the manual sensors showed a significant flood treatment × time interaction ($F = 1.7$; $P < 0.03$) as well as significant main effects (flood treatment: $F = 38.08$, $P < 0.0001$, time: $F = 16.98$, $P < 0.0001$).

Manual redox measures differed from those obtained by the automated system. Nearly every manual reading fell outside the calculated confidence intervals for the automated system, indicating a significant difference in the two methods of data collection. Pearson correlation coefficients were generally low with the exception of the 5-week-stagnant comparison (Table 2), the only significant correlation. Automated and manual readings for the remaining flood treatments were not correlated.

Microsite variability may account for some of the differences between automated and manual redox potential readings (Patrick, Gambrell, and Faulkner 1996; Austin and Huddleson 1999; Vepraskas and Faulkner 2001, Eshel and Banin 2002; Mansfeldt 2003; D'Amore, Stewart, and Huddleston 2004). For example, placement of an electrode near organic matter that is actively undergoing microbial oxidation will result in observation of lower redox potentials (Vepraskas and Faulkner 2001). Manual readings were taken near the automated sensors within a channel but not in the exact location. Differences in soil properties and drift in calibration may also have contributed to the variability observed in the automated readings. In addition, variability in manual readings may have occurred from a difference in electrode placement because more than one person

Table 2. Pearson correlations between ORP measurements using automated and manual OPR systems with different flood treatments

Flood treatment	r^2	P value
3-week-flowing	0.20	0.20
5-week-flowing	0.33	0.08
5-week-stagnant	0.63	0.01
Control	0.07	0.47

conducted the field sampling. Even a slight difference in electrode location could create substantial differences in redox potential (Vepraskas and Faulkner 2001). Installation of additional electrodes at various locations within the channels might help to reduce variability and improve the predictive ability of our system. Patrick, Gambrell, and Faulkner (1996) recommended at least triplicate electrodes at each depth, whereas Vepraskas and Faulkner (2001) recommended 5–10.

Soil pH

Preliminary examination of the automated pH data revealed unexpected treatment effects for several channels. Flooding should result in the convergence of pH values to neutrality (i.e., pH between 6.7 and 7.2) (Mitsch and Gosselink 2000); however, in some cases, increases in pH to values of at least 8 were observed. In addition, anomalous values were detected in several of the channels; these anomalies included negative pH values as well as pH values greater than 14. The anomalous data (i.e., all pH readings less than 4 or more than 8) were removed from the data set prior to statistical analysis.

Anomalies in pH data may be related to three factors: (i) dry soil conditions in the control channels, (ii) a period of heavy rain midway through the experimental period, and (iii) damage to the conduits or the cables. First, soil pH electrodes are designed to measure pH from soil slurries, not from dry soil. The control channels, which were relatively dry at the beginning of the experiment, were among those that were the most highly variable. Second, in the remaining channels with anomalous data, the problematic readings began during a period of heavy rain events (Figure 2a). It is possible that water leaked into the conduits because of higher than normal water levels in the channels, causing problems with signal transduction. These channels did not recover to expected readings after these rain events; for example, in channel 10, pH readings were negative from the period of the heavy rains until termination of the experiment. Finally, channels with anomalous data are adjacent to each other; specifically channels 6–10 all had problematic pH readings. Although the sensors in these channels were not connected to a single, common datalogger, some of the cables run through the same conduits (i.e., cables for channels 7 and 8 are in the same conduit and cables for channels 9 and 10 are in the same conduit). There may be problems within these conduits (leakage or rodent damage) that could have contributed to the anomalous data.

No general convergence toward neutrality was observed for this system regardless of sensor type (Figure 6). In fact, no trends in pH with flood treatment or over time were obvious. Both manual and automated readings of pH showed high variability; of note is the wide range of values recorded

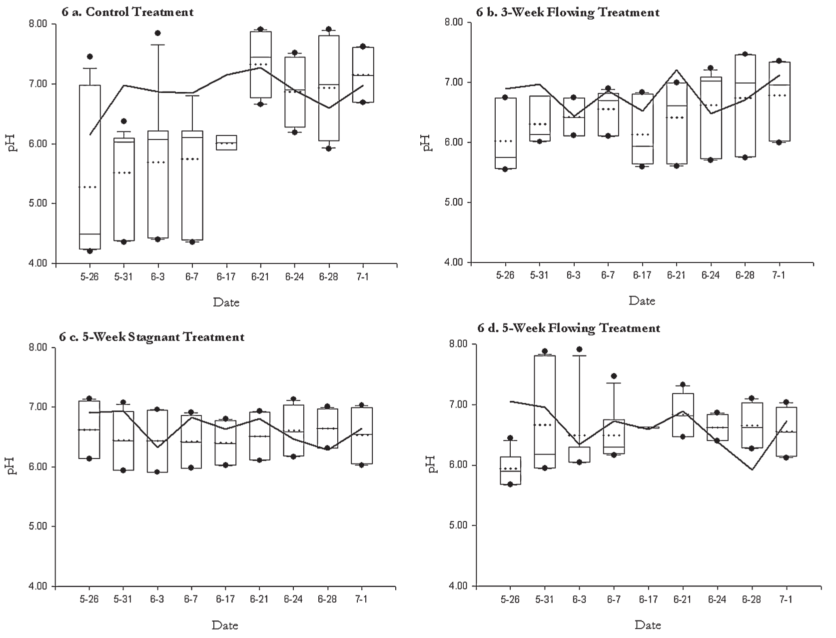

Figure 6. Soil pH measured by the automated sensors (box plots) and manual sensors (line) for a 6-week period (May 26–July 4 2005). For automated sensors, anomalous data points were removed (i.e., pH readings less than 4 or more than 8), then weekly averages were calculated by combining hourly values between 7 a.m. and 12:00 p.m. from replicate channels. For replicate channels, the boxes depict the 25th and 75th percentiles, the whiskers indicate 10th and 90th percentiles, the solid line represents the median, and the dotted line represents the mean. Manual readings were measured once during the period sampled by the automated sensors; data points represent the average reading for replicated channels under the designated treatments.

by the automated sensors (Figure 6). Mean pH varied little from treatment to treatment or from week to week.

The ANOVA results for the automated sensor data revealed no significant differences in pH due to flood treatment, time, or flood treatment $\times$ time. However, ANOVA results for the manual sensor data revealed a significant effect of time ($F = 2.99$; $P < 0.01$), but there were no significant differences among flood treatments and no interaction effect. Manual pH readings were different than those recorded by the automated system. Nearly every manual reading fell outside the calculated confidence intervals for the automated system, indicating a significant difference in the two methods of data collection. Pearson correlation coefficients were generally low (Table 3), indicating a lack of relatedness between the two measurement approaches. Again, microsite variability may have contributed to the differences in pH recorded by the automated and manual systems.

Table 3. Pearson correlations between pH measurements using automated and manual pH systems with different flood treatments

Flood treatment	r^2	P value
3-week-flowing	0.01	0.83
5-week-flowing	0.10	0.40
5-week-stagnant	0.25	0.17
Control	0.21	0.22

CONCLUSIONS

The information gathered by the automated sensors will be relevant to the other researchers in the FTL as they attempt to explain differences in flood tolerance of woody hardwoods and herbaceous groundcovers. Although not its intent, this study does reveal some of the challenges to working in an outdoor laboratory, most notably the difficulty in achieving true control conditions. Soil volumetric water content readings, for example, might suggest seepage of flood waters through the berms separating adjacent channels, resulting in the saturation of soils within the control channels. In addition, redox potentials and dissolved oxygen readings indicate that assumptions made about particular flood treatments may not be valid. In this case, the 5-week-stagnant treatment was more aerated than the 5-week-flowing treatment, an observation that may help explain apparent anomalous results in flood tolerance experiments. The ability to quantify parameters such as redox potential, dissolved oxygen content, and volumetric water content will provide more information about the actual impact of flooding on the environmental conditions than simply quantifying flood duration and flow rate.

Although this study did reveal potential problems with the automated sensors, the convenience of use and ability to capture variation due to factors such as treatment and weather make the automated system preferable. The automated sensors allow for greater sample frequency without disrupting the system, for capturing variation that would otherwise be missed with periodic manual measurement, and for reduced labor needs. The system used in this study was not without some disadvantages, and potential cable and/or sensor problems will have to be worked out prior to the next flood cycle. Among the possible flaws were lack of opportunities for periodic calibration, potential degrading of the electrode membranes due to changes in environmental conditions, lack of correlation between automated and manual monitoring, and the high initial cost of purchasing and maintaining the system. Results of this study suggest that greater numbers of sensors may be needed in each channel, because of the high variability observed in soil characteristics, such as redox potential. In addition, investment in an automated system may only be appropriate at sites where there is a long-term research commitment.

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